Electromagnetic Counterparts to Neutron Star Binary Mergers

Shota Kisaka

(Aoyama Gakuin Univ.)

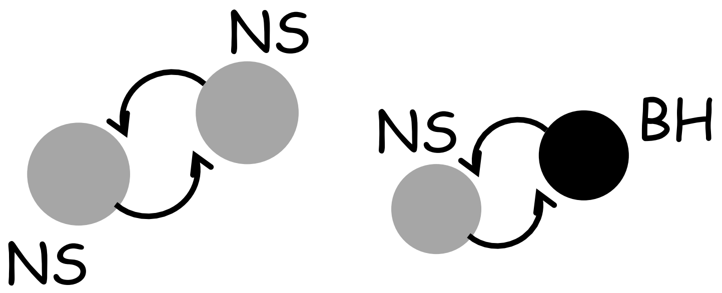
Collaborators : Kunihito Ioka, Takashi Nakamura,
Ehud Nakar, Takanori Sakamoto

Merger of Neutron Star Binaries

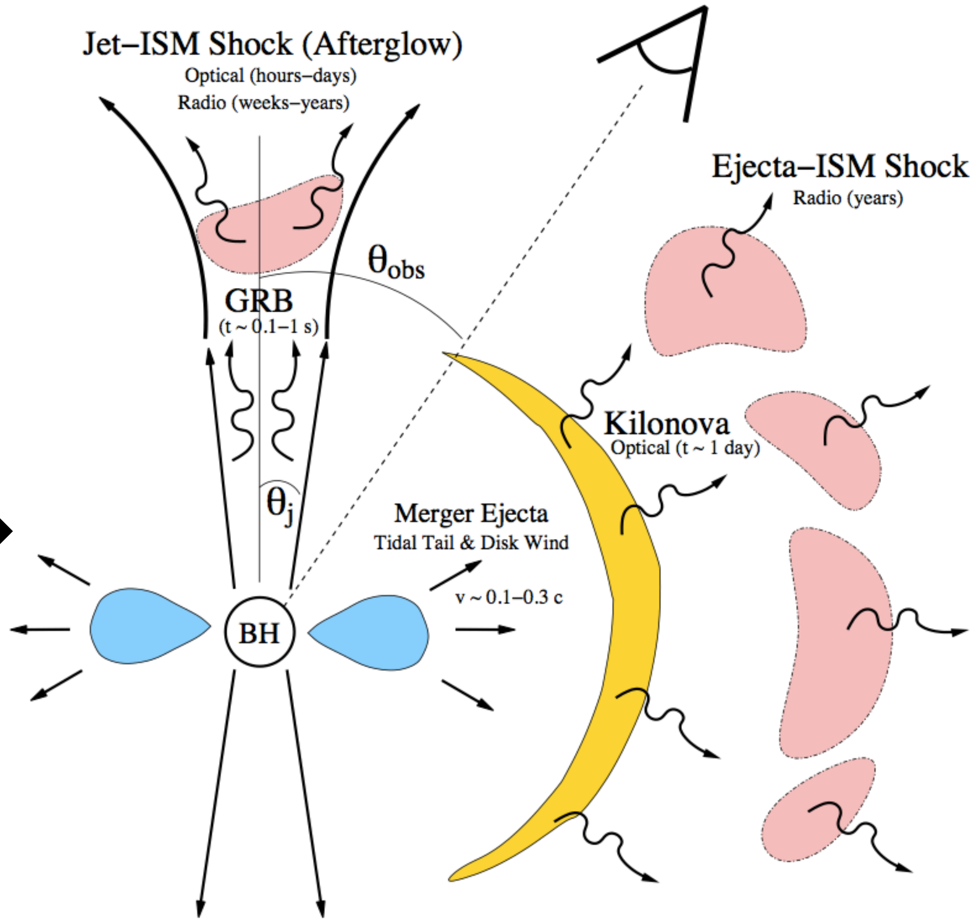
EM counterparts to GW sources are important to maximize scientific returns from the detection of GWs.

Metzger & Berger 12

e.g.,
- Localization
- Origin of short GRBs
- Equation of state
- *r*-process enrichment

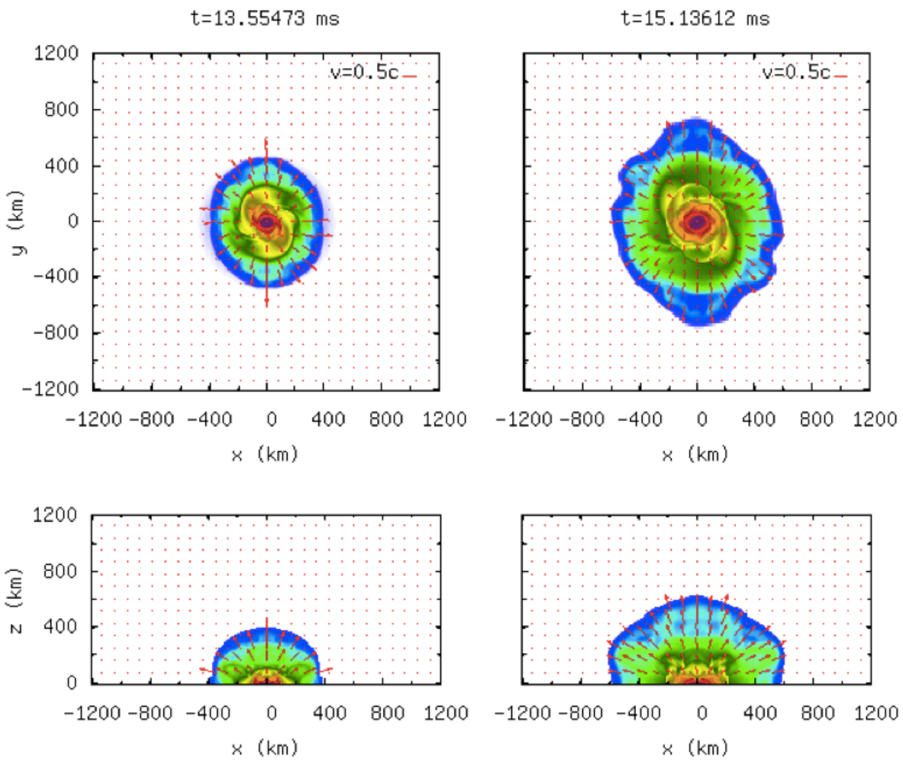


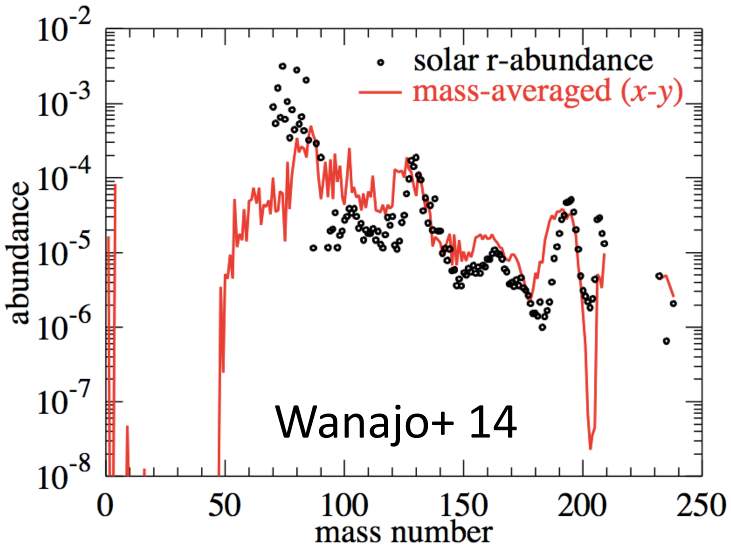
NS binary



Merger Ejecta

Hotokezaka+ 13





Bounded mass

$$M_{\rm d} \sim 10^{-1} M_\odot$$

Ejecta mass

NS-NS: $M_{\rm ej} \sim 10^{-4} - 10^{-2} M_\odot$

BH-NS: $M_{\rm ej} \lesssim 10^{-1} M_\odot$

Ejecta velocity

$$v_{\rm ej} \sim 0.1 - 0.3c$$

Homologous expansion

$$R_{\rm ej} \sim v_{\rm ej} t$$

r-process nucleosynthesis

Neutron-rich Ejecta

$\Rightarrow T_{\rm n-capture} < T_{\beta-{\rm decay}}$

Energy Sources

- **Rotation energy:**

$$\sim 10^{53} \left(\frac{M_{\rm BH}}{3M_\odot}\right) \text{ erg} \qquad (a/M_{\rm BH} = 0.5)$$

- **Disk gravitational energy:**

$$\sim 10^{52} \left(\frac{M_{\rm d}}{10^{-1}M_\odot}\right) \text{ erg}$$

- **Ejecta kinetic energy:**

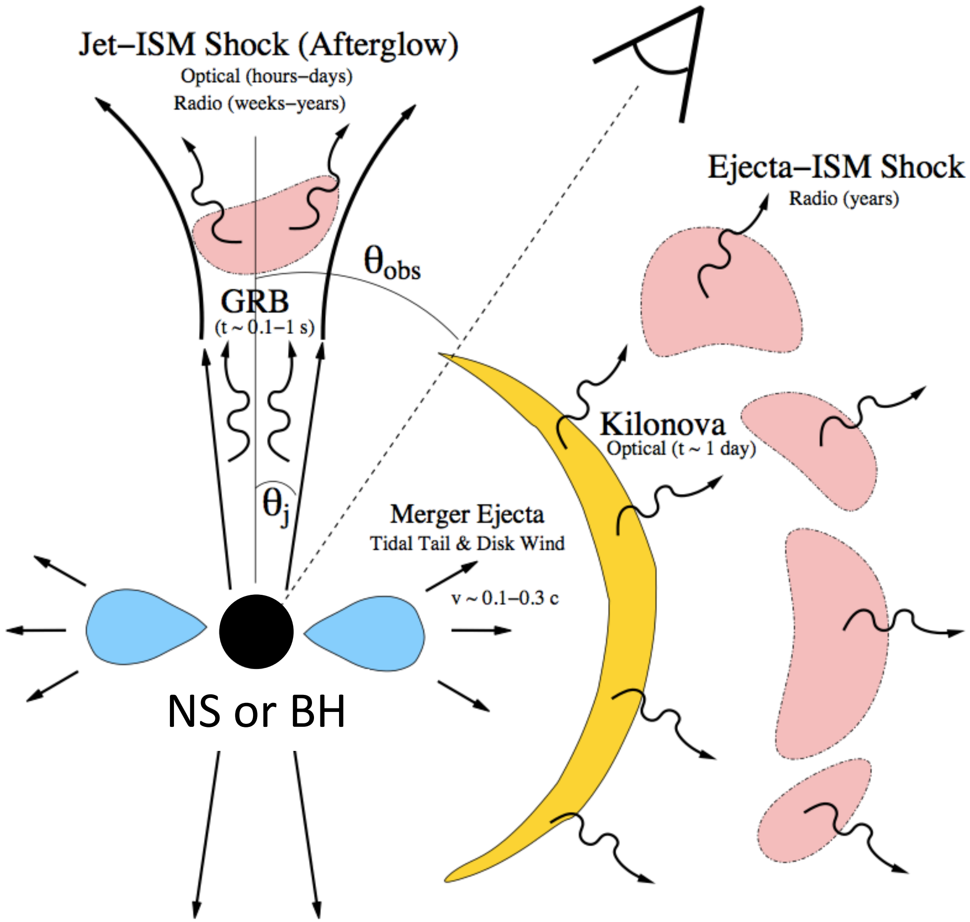
$$\sim 10^{51} \left(\frac{M_{\rm ej}}{10^{-2}M_\odot}\right) \left(\frac{v_{\rm ej}}{0.3c}\right)^2 \text{ erg}$$

- **Radioactivity:**

$$\sim 10^{49} \left(\frac{\epsilon}{10^{-3}}\right) \left(\frac{M_{\rm ej}}{10^{-2}M_\odot}\right) \text{ erg}$$

- Magnetic field:

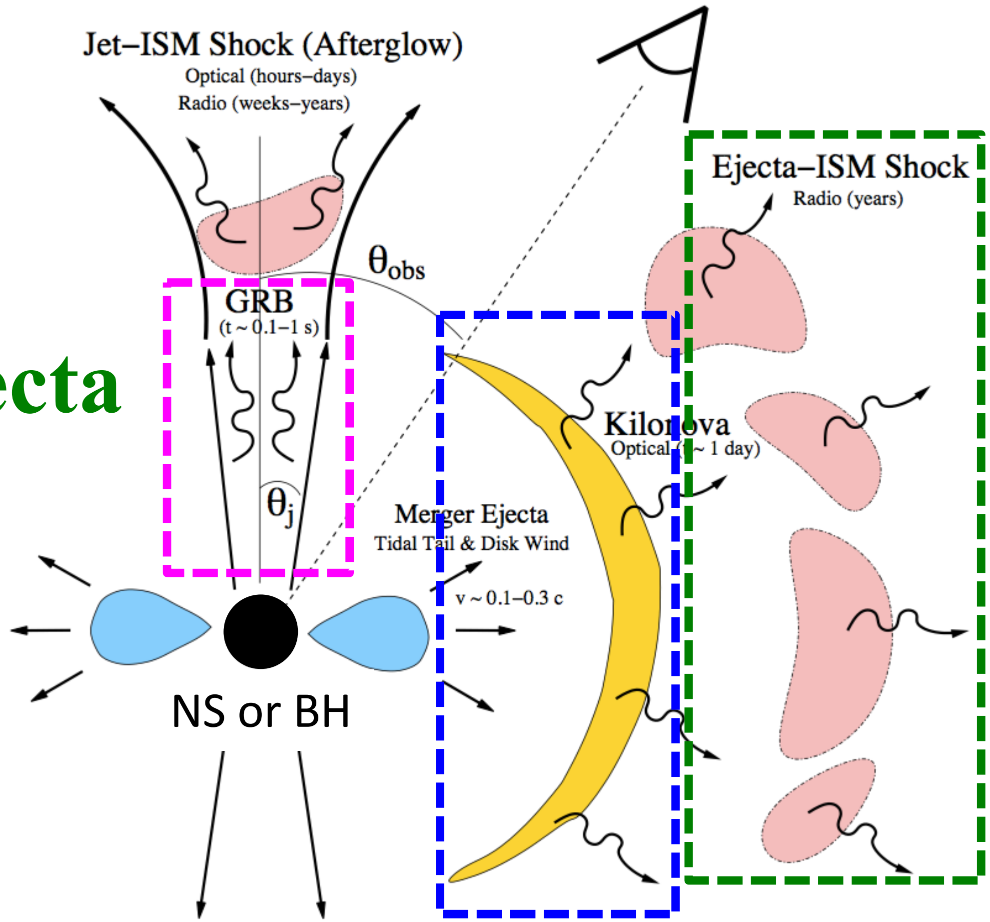
$$\sim 10^{48} \left(\frac{B}{10^{15}\text{G}}\right)^2 \text{ erg}$$



Metzger & Berger 12

EM Counterparts

- **Gamma-ray Bursts**
  $t < 10^6$ s
  Rotation/disk grav. energies
- **Macronovae/Kilonovae**
  $t \sim 10$ day
  Radioactivity (?)
- **Remnants of Merger Ejecta**
  $t \sim$ yr
  Ejecta kinetic energy



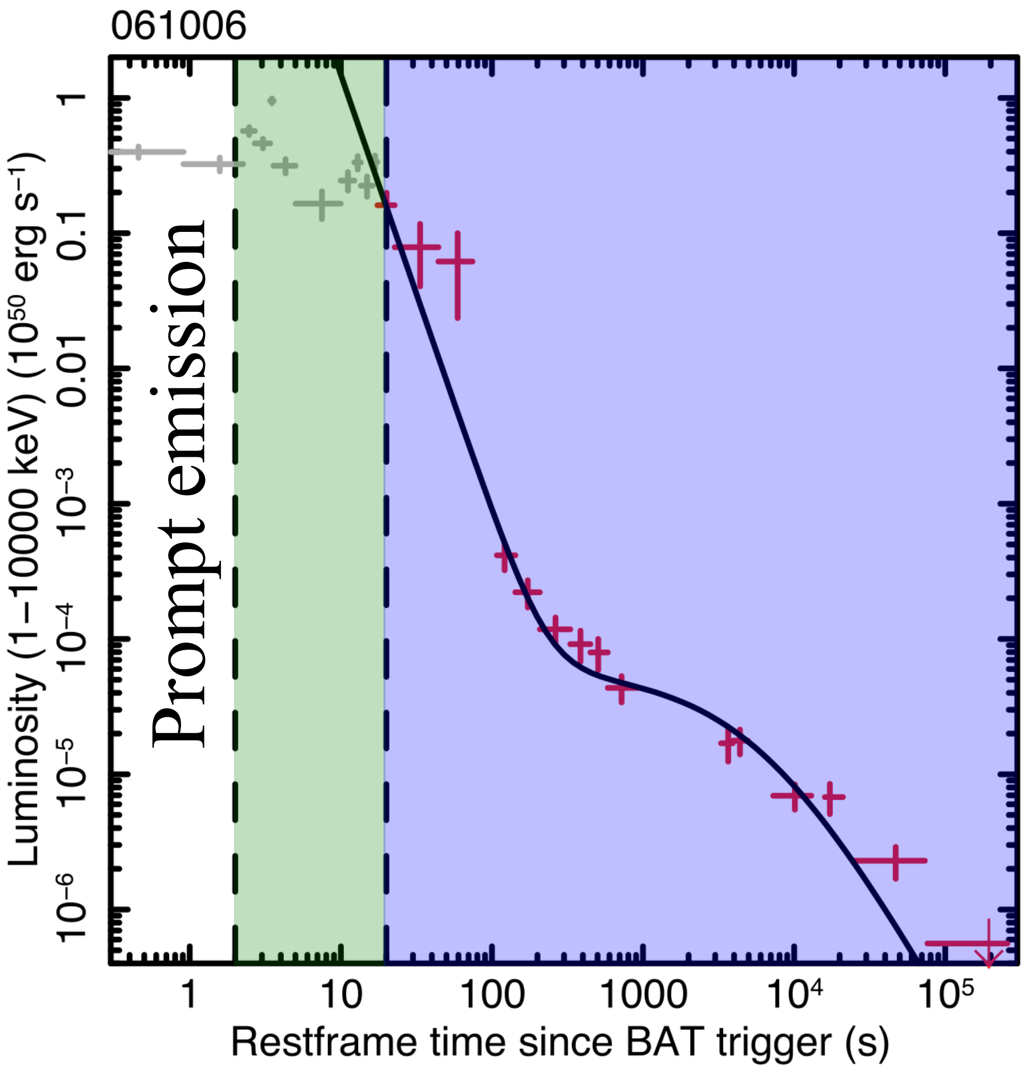
Metzger & Berger 12

Gamma-Ray Bursts

Light Curve

Extended emission : L ~ 10^{48} erg/s, T ~ 10^{2} s

Plateau emission : L ~ 10^{45} erg/s, T ~ 10^{4} s



Gompertz+ 13

cf. Prompt emission

L ~ 10^{50} - 10^{51} erg/s

T ~ 0.1 – 1 s

Total energy is comparable

~ 10^{50} - 10^{51} erg

<u>NS scenario</u> (Gompertz+ 13)

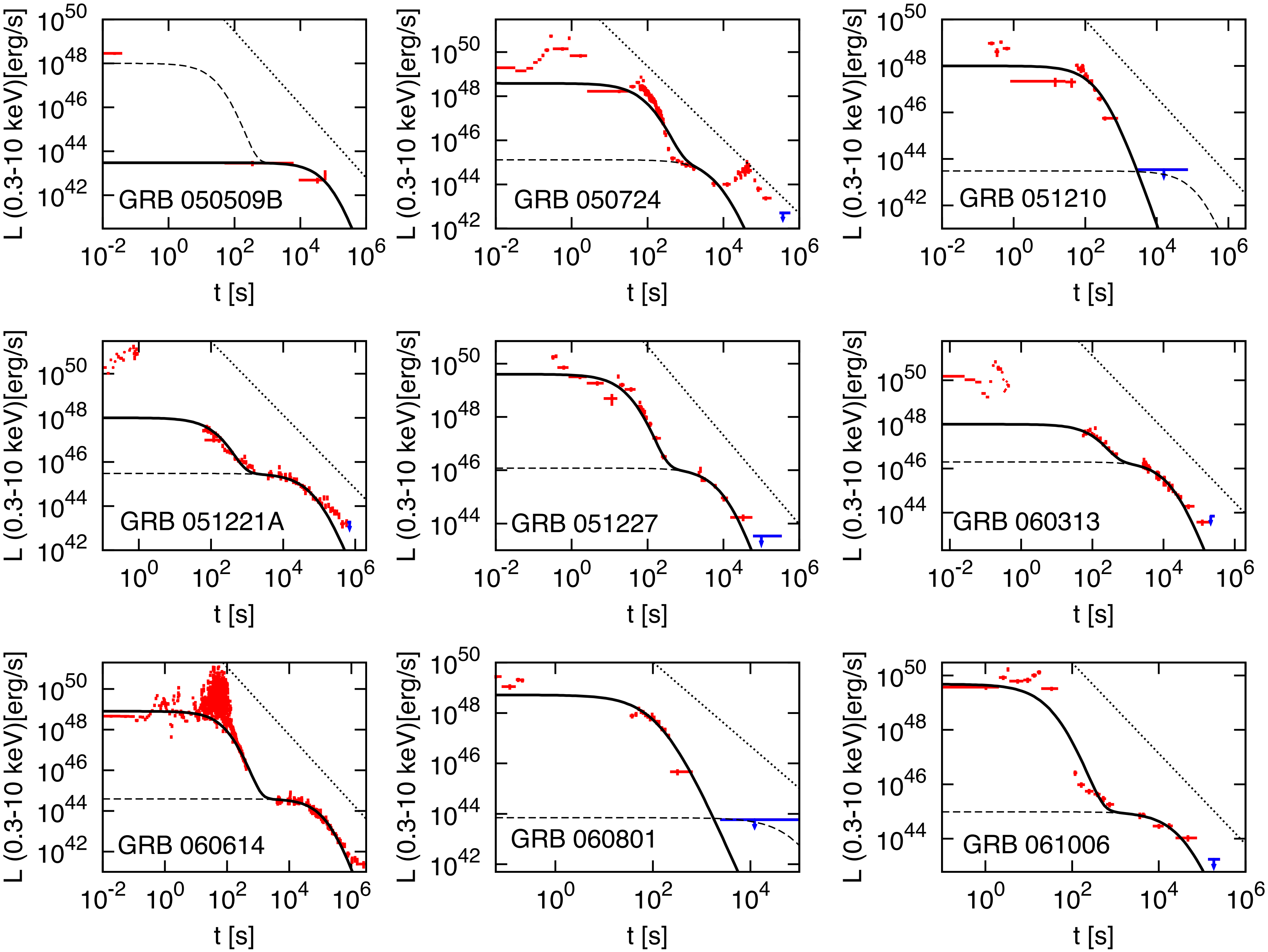
(Propeller → wind)

<u>BH scenario</u> (SK & Ioka 15)

(BZ jet + B-field evolution)

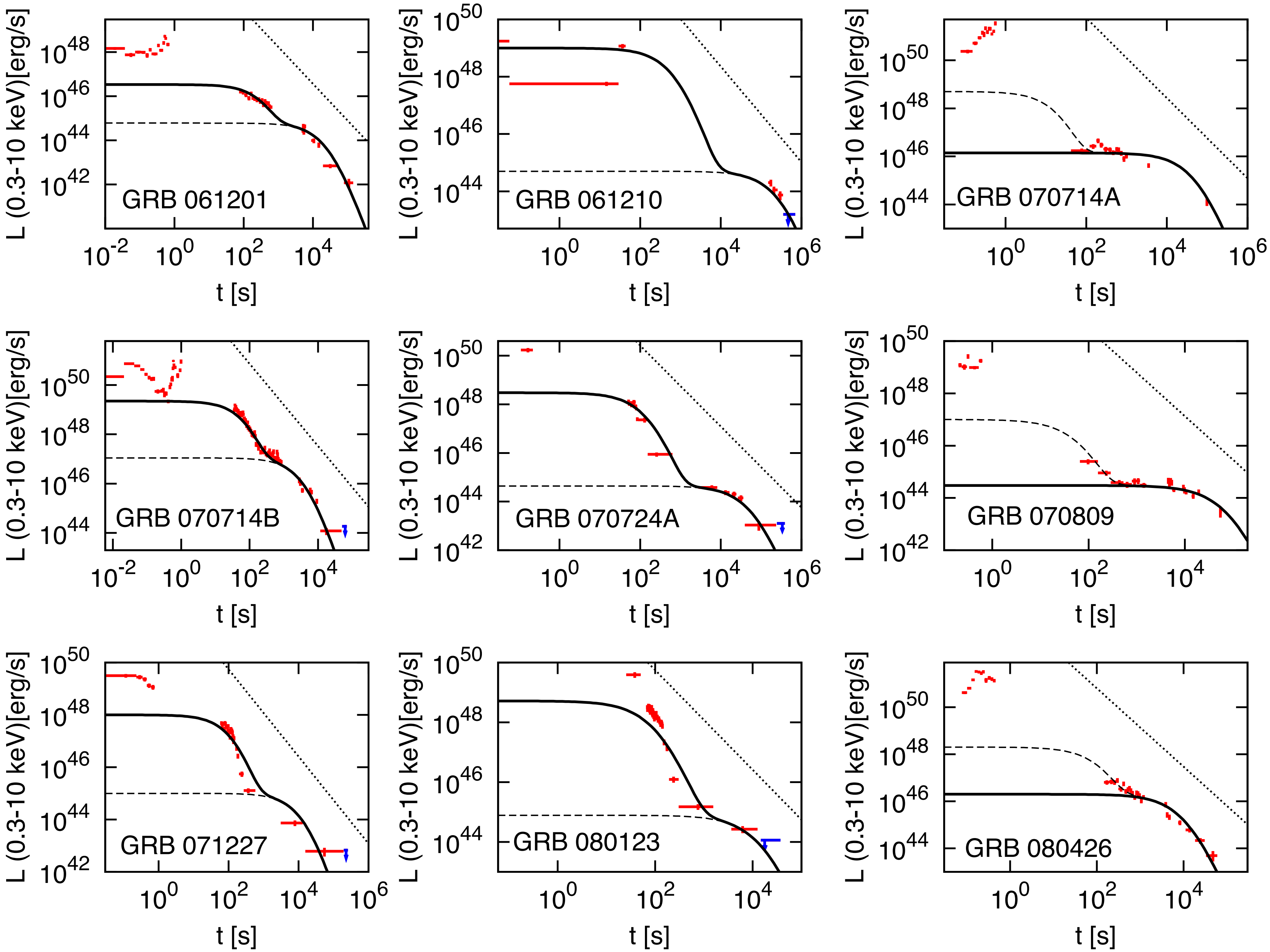
Light Curves

Model : SK & Ioka 15



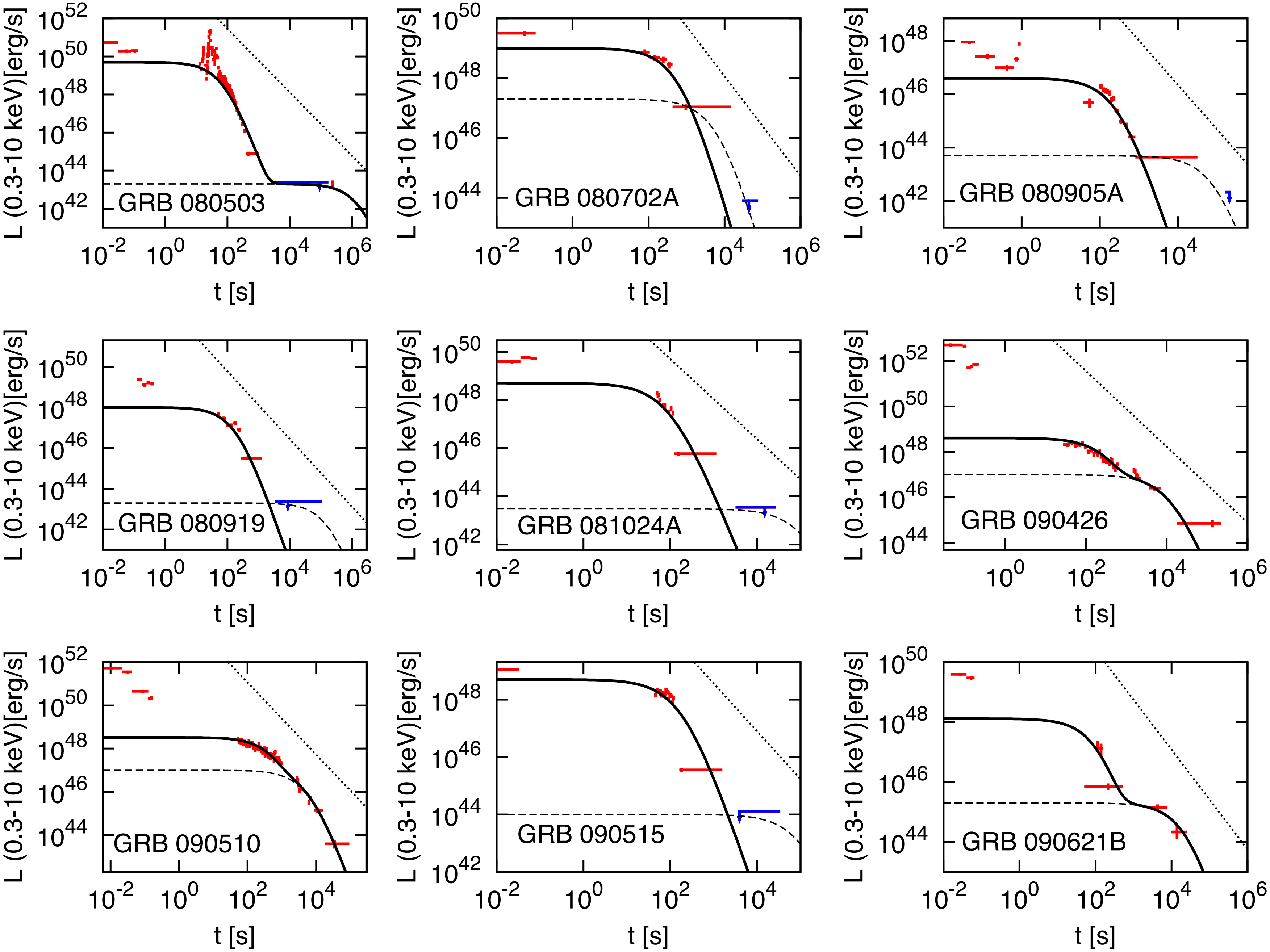
Light Curves

Model : SK & Ioka 15



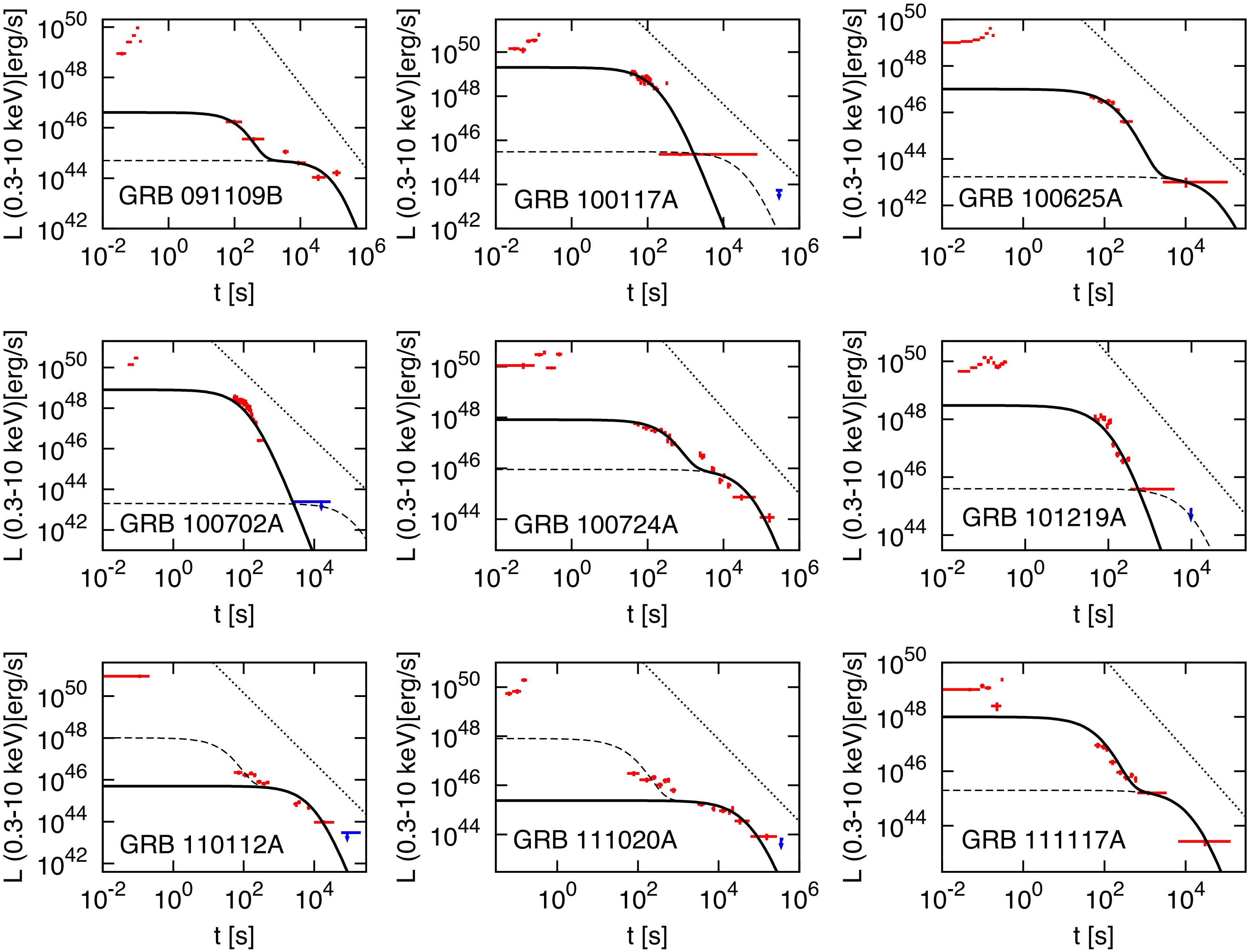
Light Curves

Model : SK & Ioka 15



Light Curves

Model : SK & Ioka 15



Light Curves

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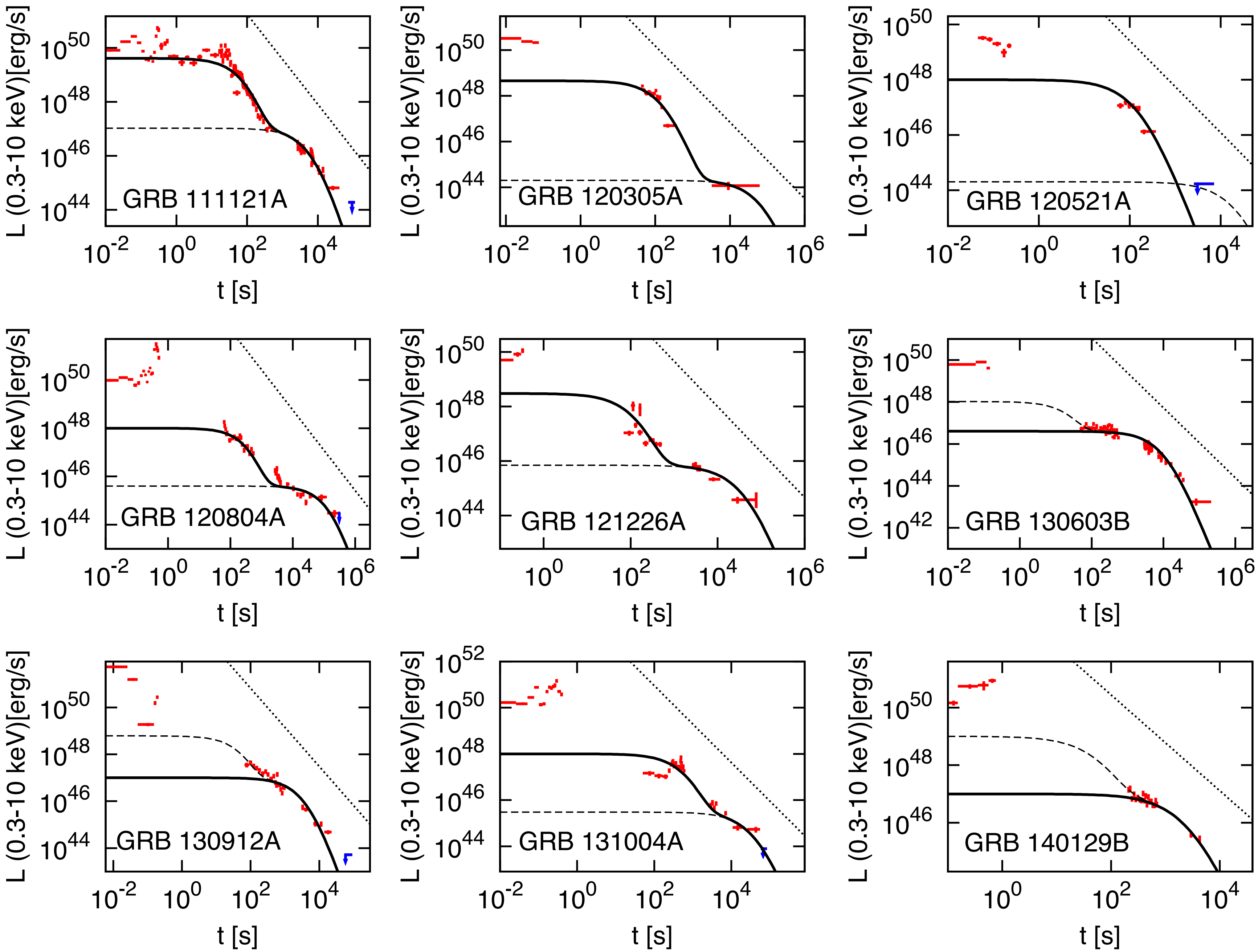

Light Curves

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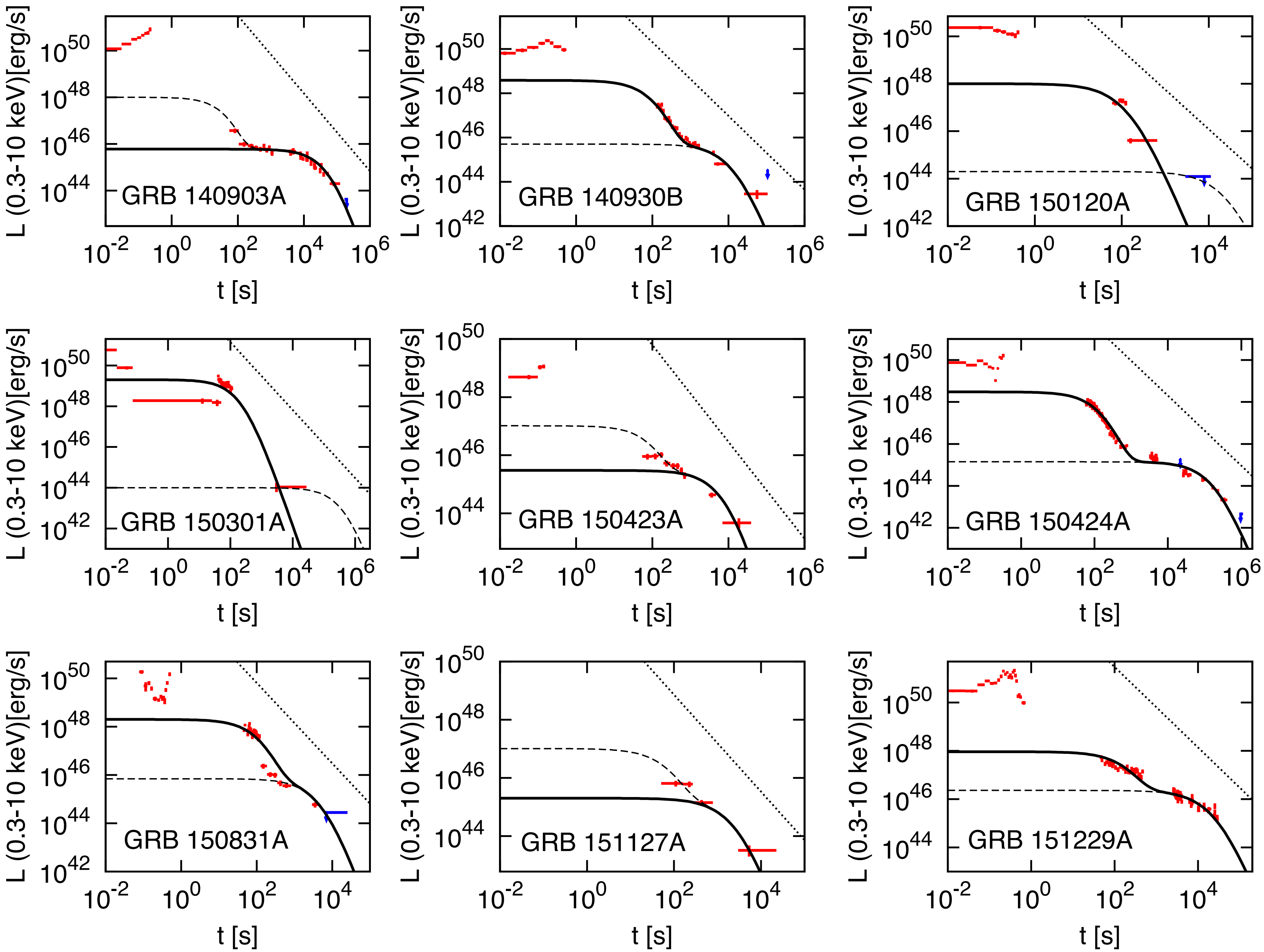
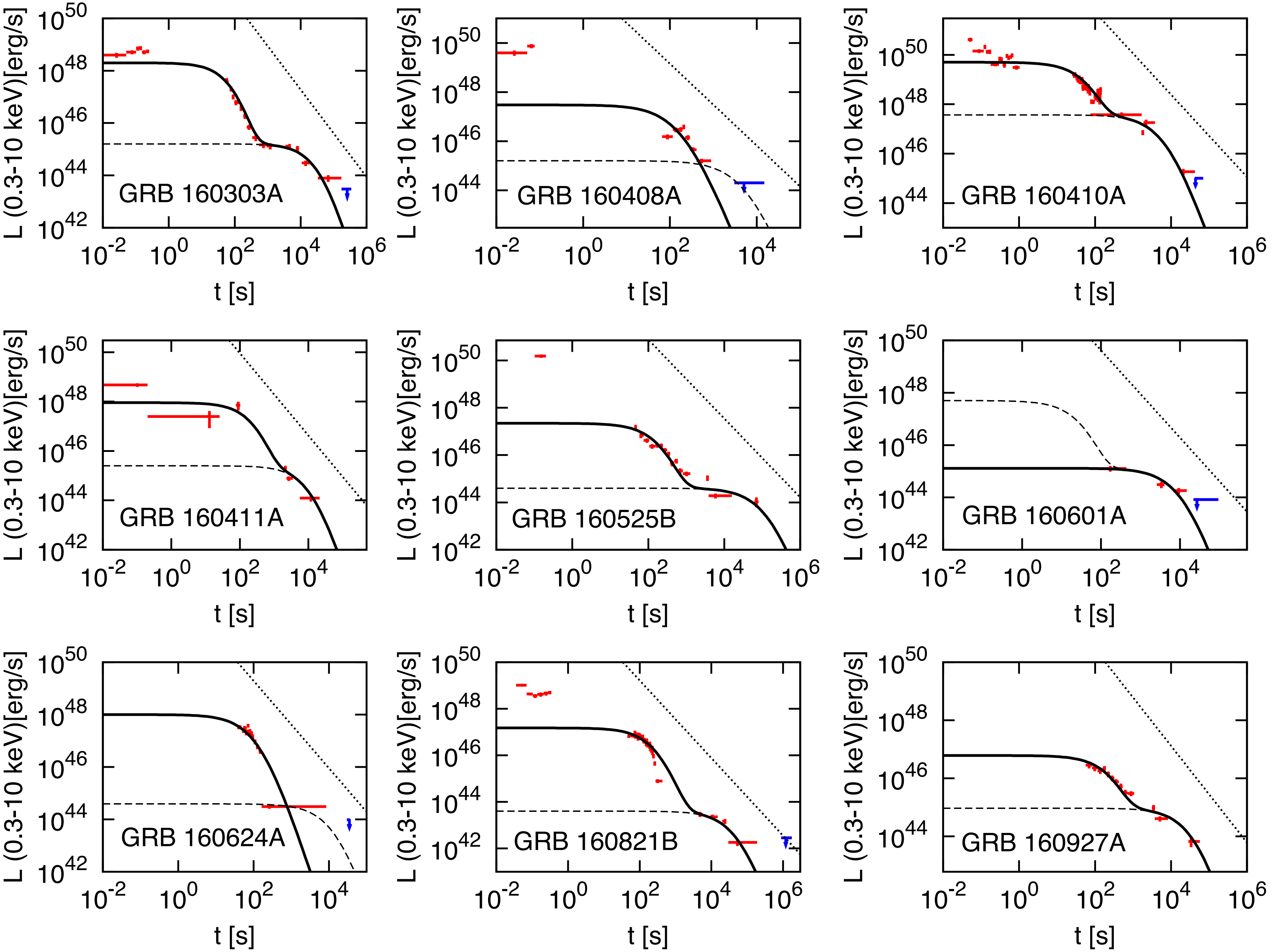


Light Curves

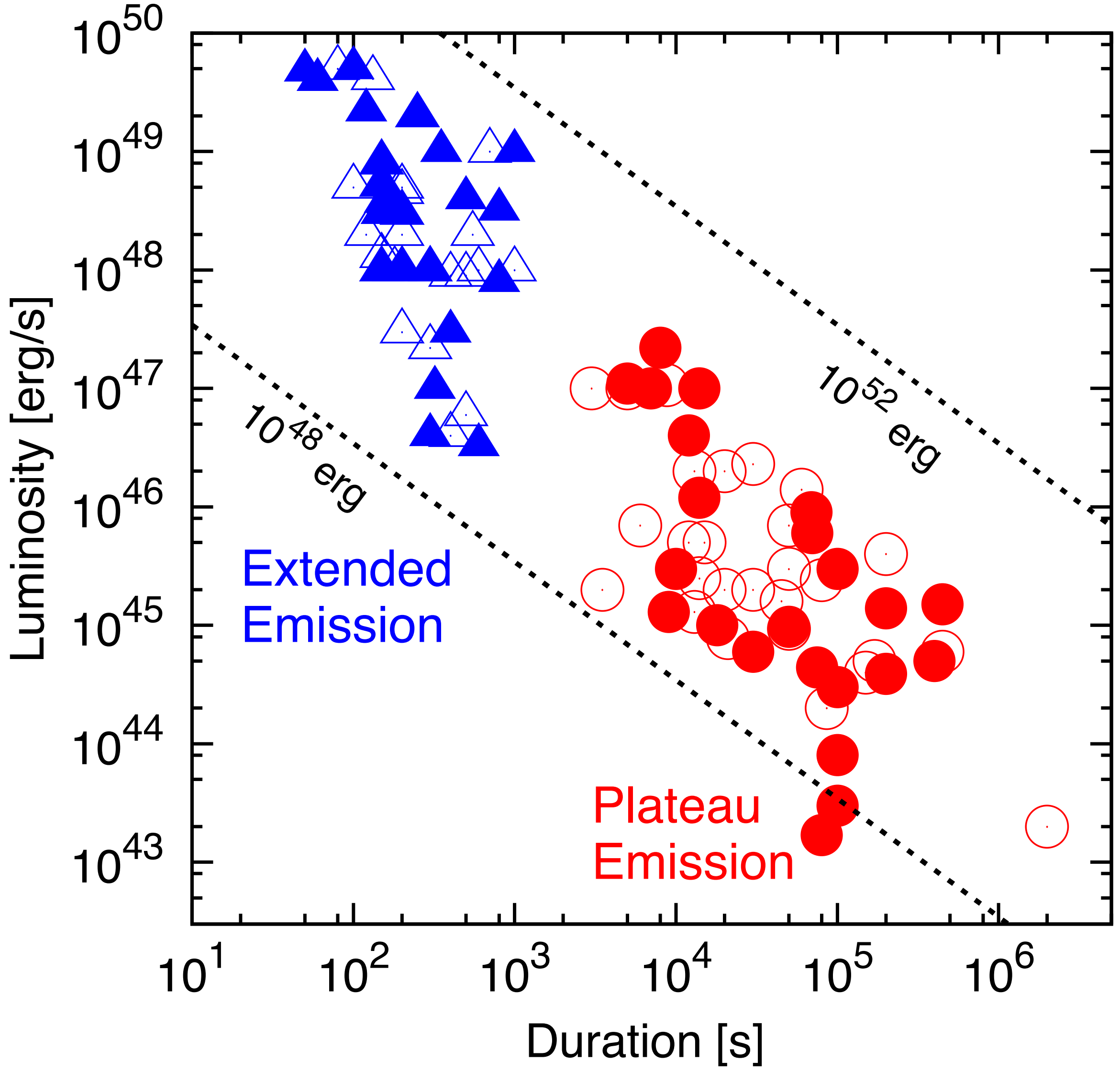
Model : SK & Ioka 15



Luminosity and Duration

Extended emission : L ~ 10^{47}-10^{50} erg/s, T ~ 10^2 – 10^3 s

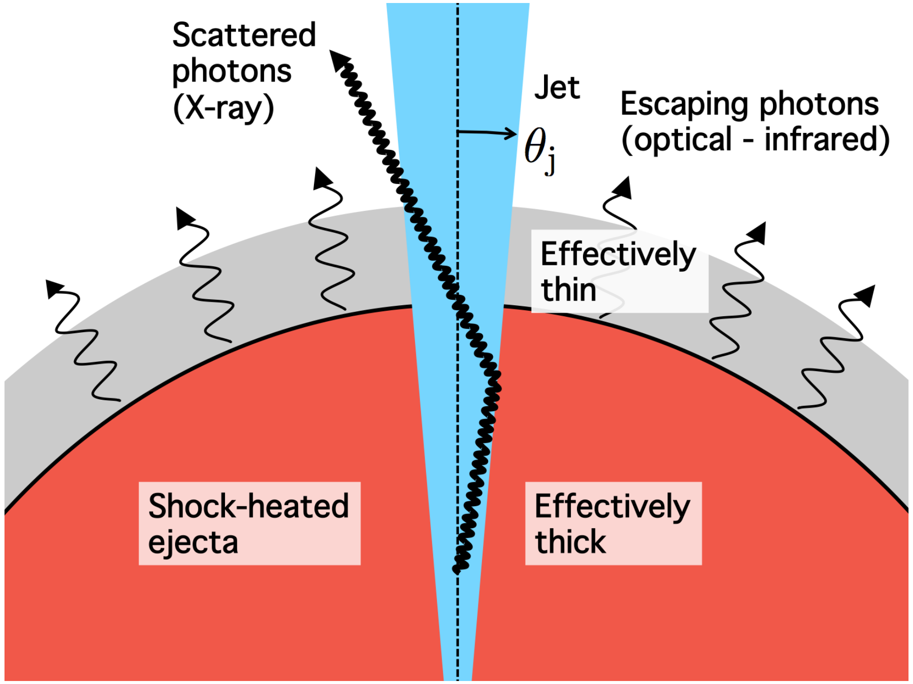
Plateau emission : L ~ 10^{43}-10^{47} erg/s, T ~ 10^4 – 10^5 s



Scattering

- Emission region locates inside the ejecta, $r_e < r$.
- Optical depth $\tau >> 1$.

SK, Ioka & Nakamura 15



Emission region

$$r_e \sim \Gamma^2 c\Delta t$$

$$\sim 3 \times 10^{12} \left(\frac{\Gamma}{10}\right)^2 \left(\frac{\Delta t}{1\mathrm{s}}\right) \ \mathrm{cm}$$

Ejecta

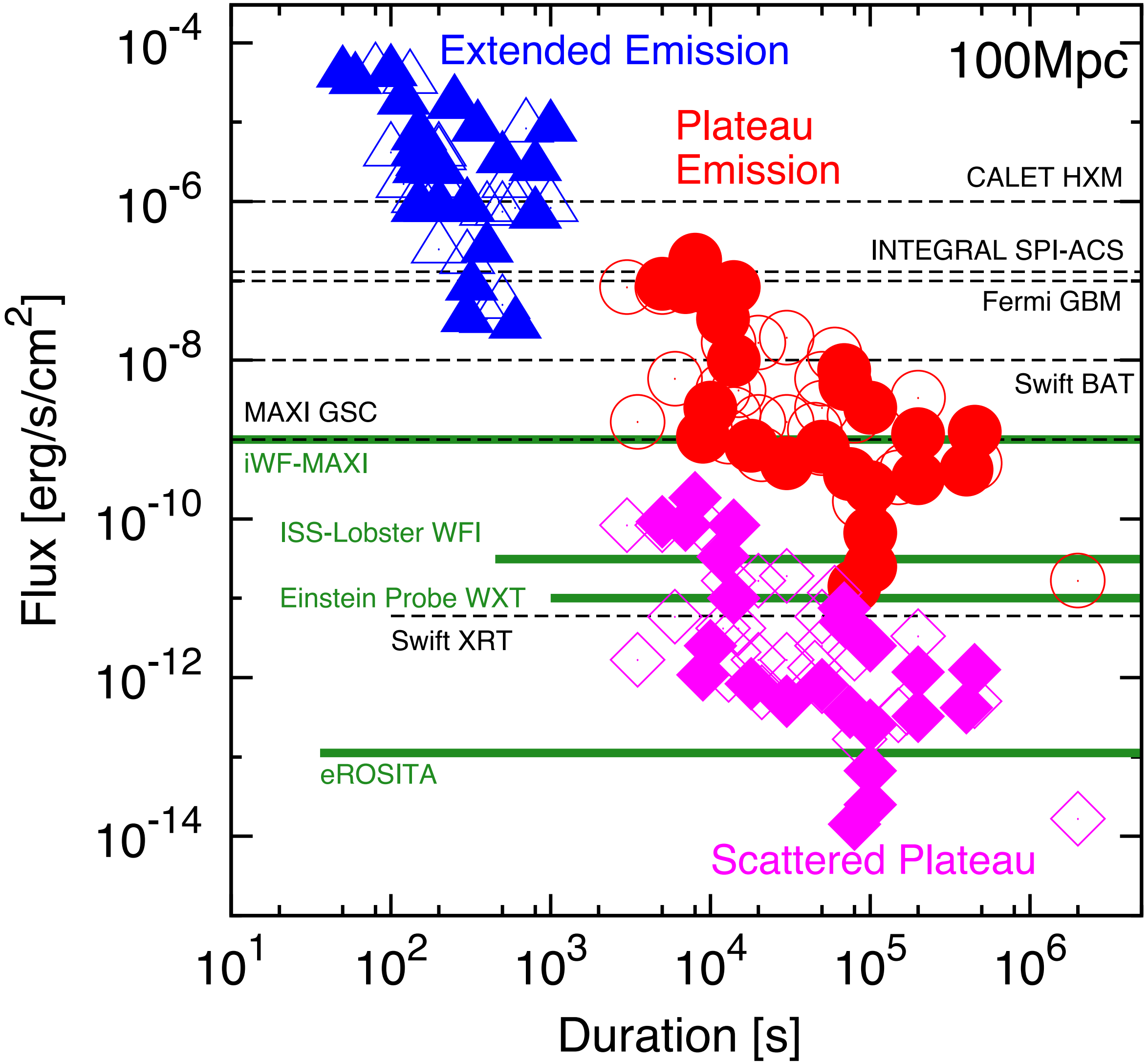
$$r \sim vt$$

$$\sim 3 \times 10^{13} \left(\frac{v}{0.1c}\right) \left(\frac{t}{10^4\mathrm{s}}\right) \ \mathrm{cm}$$

Optical depth

$$\tau \sim 10^2 \left(\frac{t}{10^4\mathrm{s}}\right)^{-2} \left(\frac{\bar{A}}{10^2}\right)^{-1} \left(\frac{M_{\mathrm{ej}}}{10^{-2}M_\odot}\right) \left(\frac{v}{0.1c}\right)^{-2}$$

Detectability



$\epsilon = 10^{-3}$

$L_{\rm scatter} \sim \epsilon L_{\rm pl}$

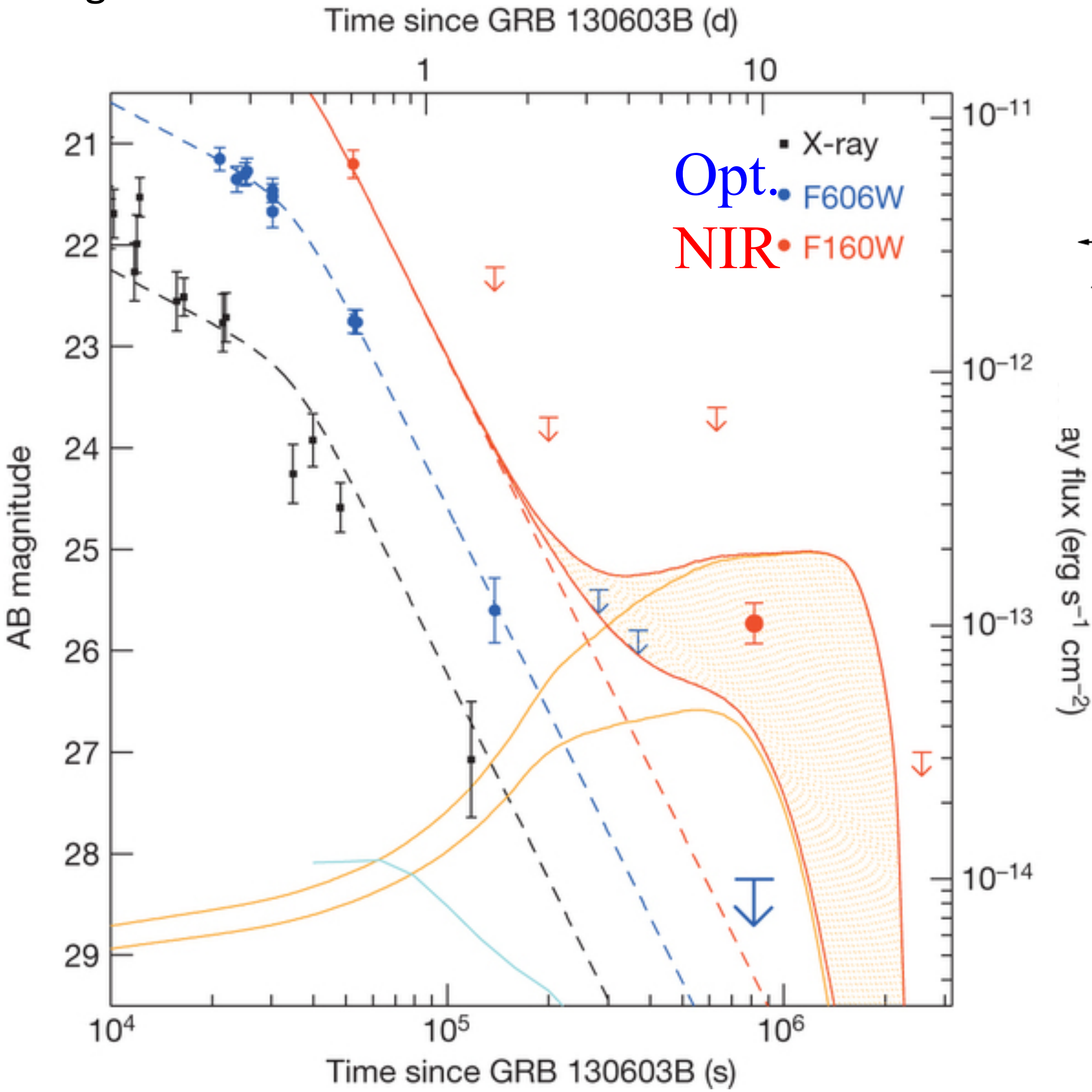
Isotropically scattered case : $\epsilon \sim 5 \times 10^{-3} (\theta_{\rm j}/0.1)^2$

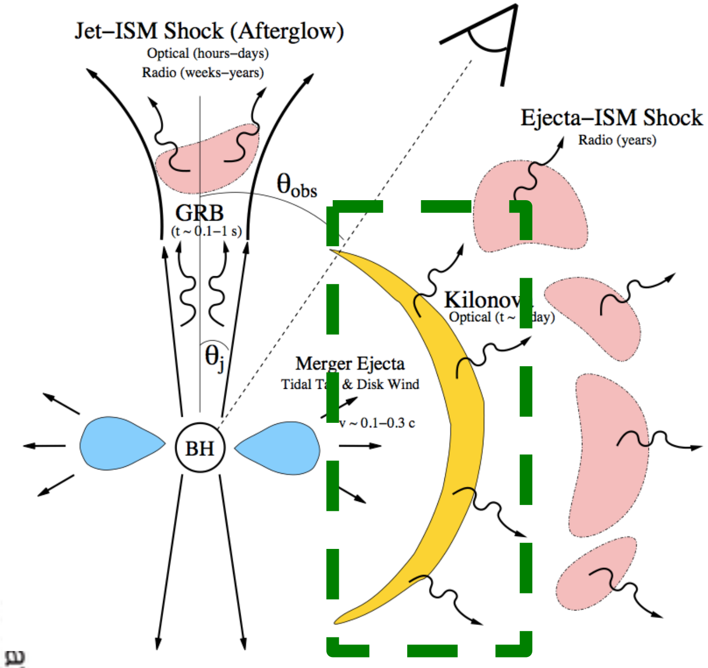
cf. $\epsilon \sim 3 \times 10^{-5} - 3 \times 10^{-4}$ (Eichler & Levinson 99)

Macronovae

Macronova Candidate

Tanvir+ 13
Berger+ 13





Metzger & Berger 12

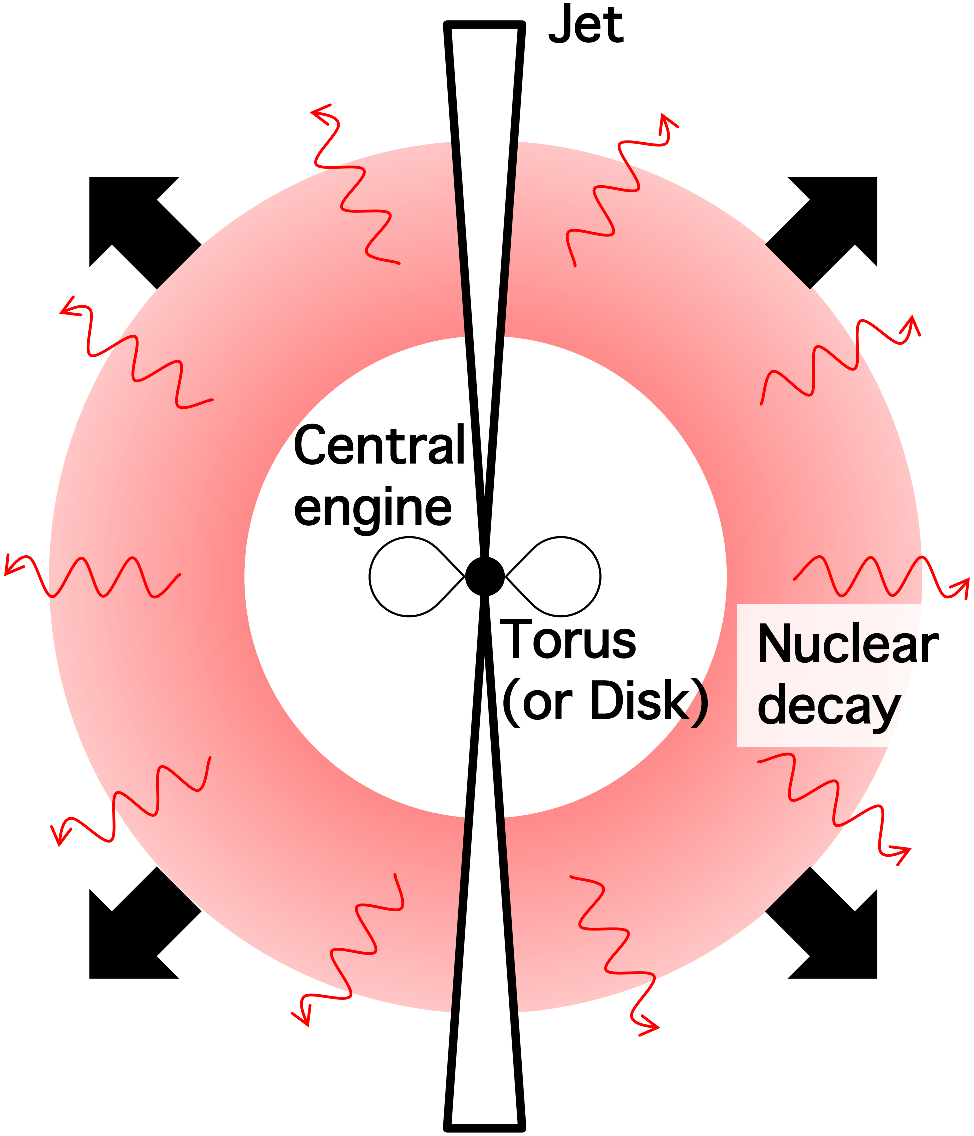
t ~ 7 day

L_{NIR} ~ 10^{41}erg/s

T < 4000 K

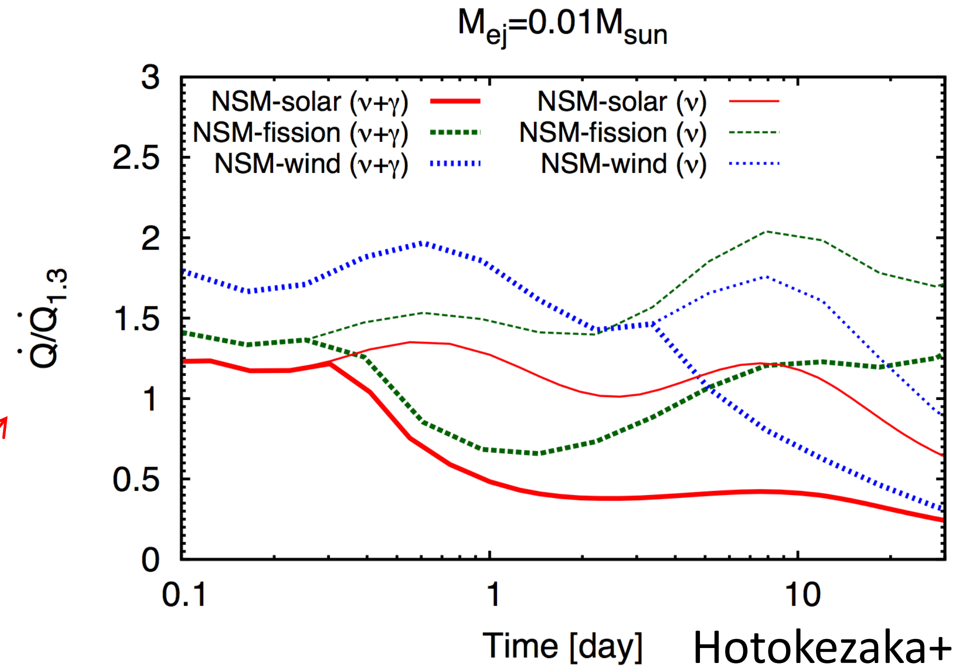
(m_r-m_j ≥ 2.5)

r-process Heating Model



Nuclear heating rate

$$\dot{Q} \sim 10^{10} \left(\frac{t}{1\mathrm{day}} \right)^{-1.3} \mathrm{erg\ g^{-1} s^{-1}}$$

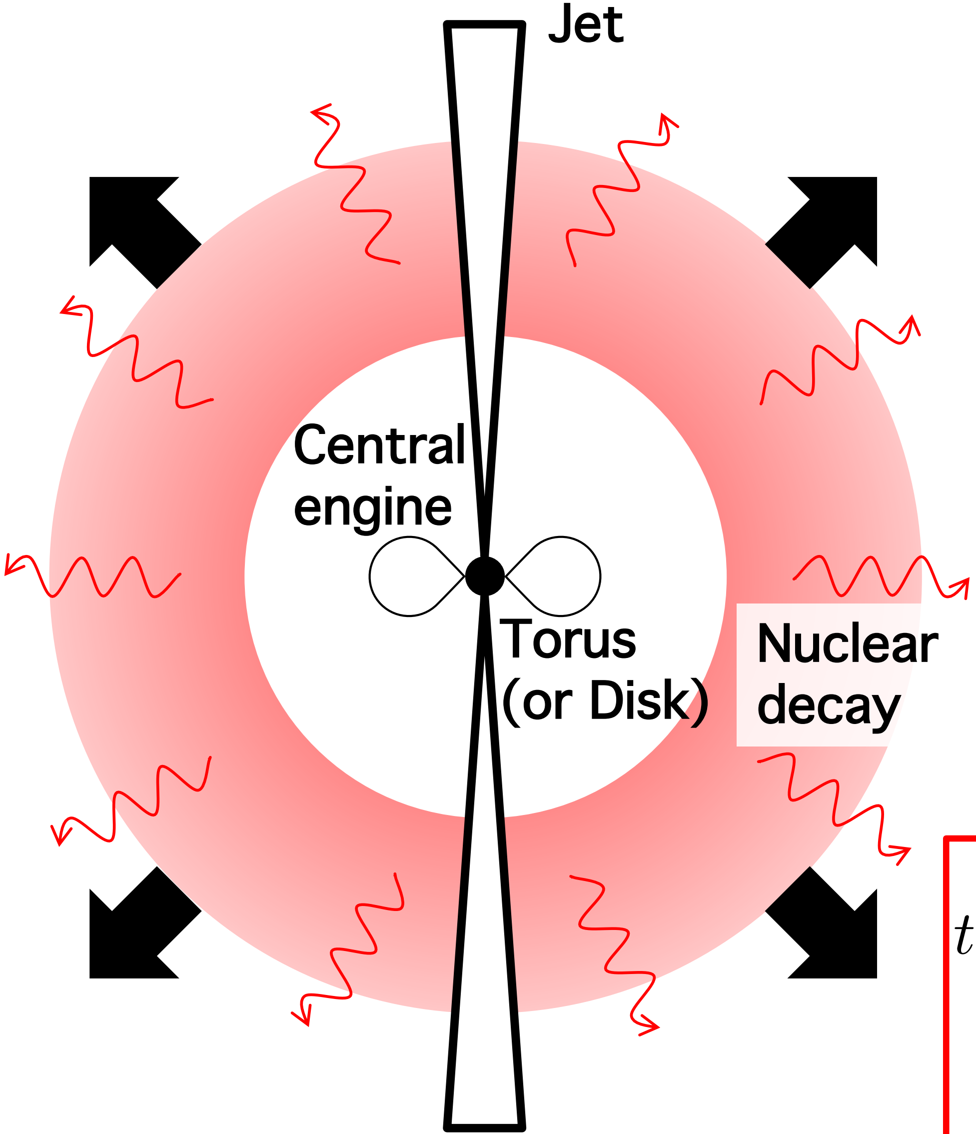


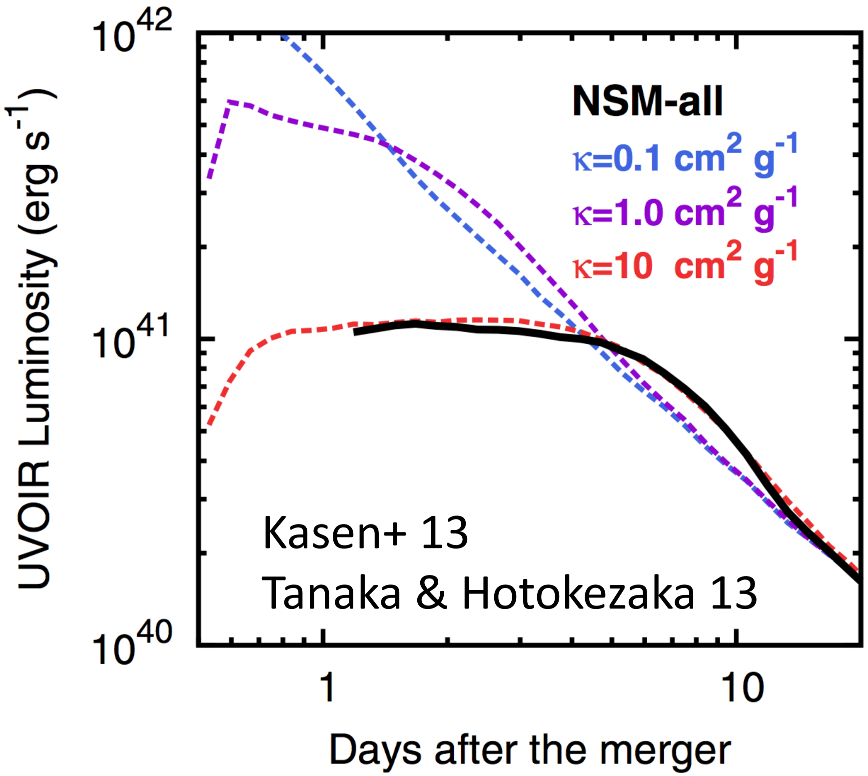
Hotokezaka+ 16

$$L \sim 10^{41}\ \mathrm{erg\ s^{-1}} \left(\frac{M_{\mathrm{ej}}}{0.05 M_{\odot}} \right)$$

r-process Heating Model

Opacity $\kappa \sim 10\mathrm{cm}^2\ \mathrm{g}^{-1}$

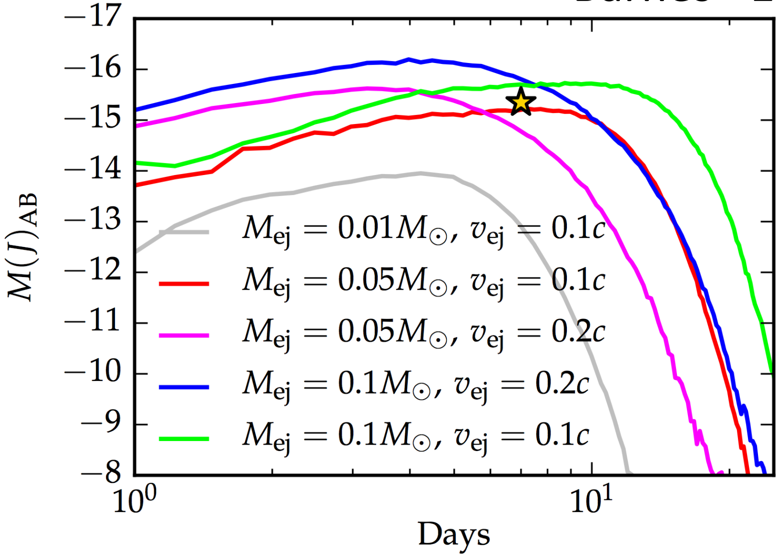




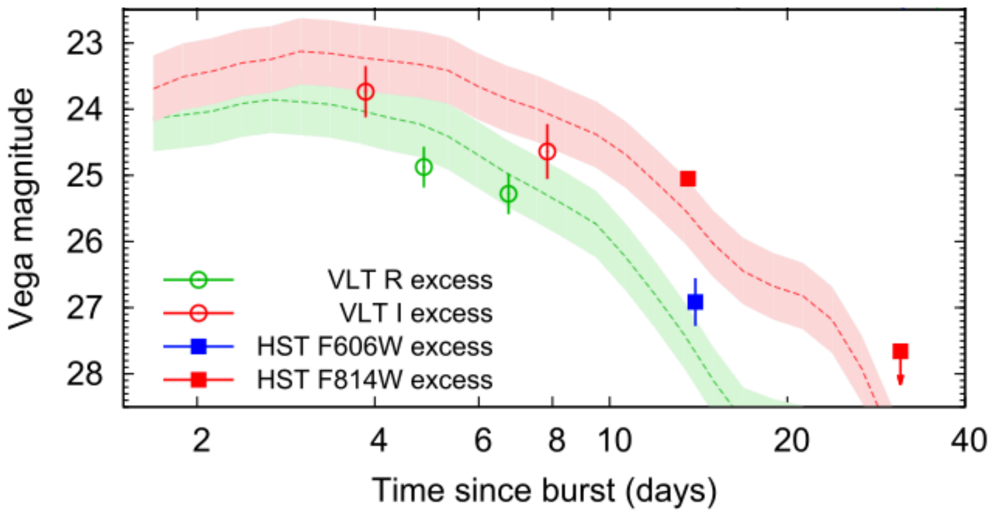
$$t_{\mathrm{peak}} \sim 7\mathrm{day} \left(\frac{M_{\mathrm{ej}}}{0.05M_\odot}\right)^{1/2} \times \left(\frac{\kappa}{10\mathrm{cm}^2\mathrm{g}^{-1}}\right)^{1/2} \left(\frac{v_{\mathrm{ej}}}{0.1c}\right)^{-1/2}$$

r-process Heating Model

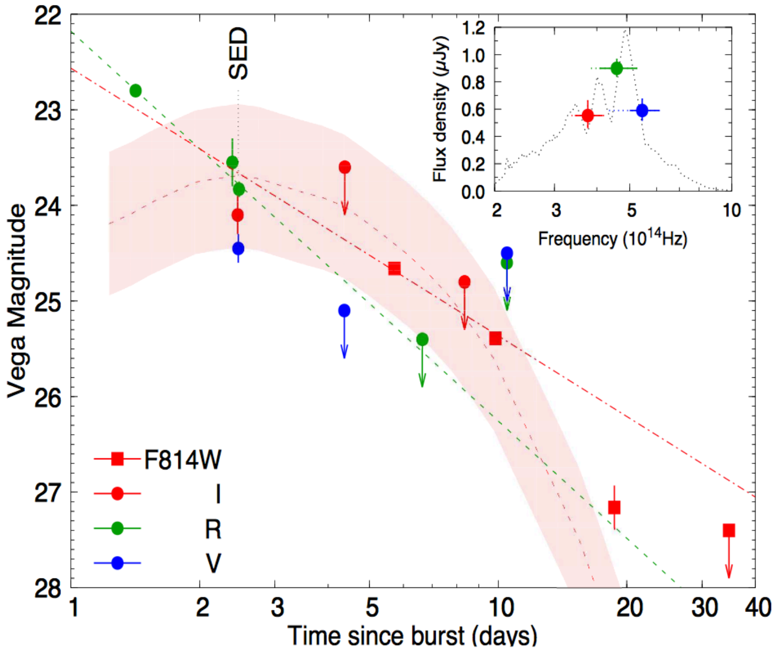
GRB 130603B Barnes+ 16



GRB 060614 Jin+ 15



GRB 050709 Jin+ 16



Light curve fitting

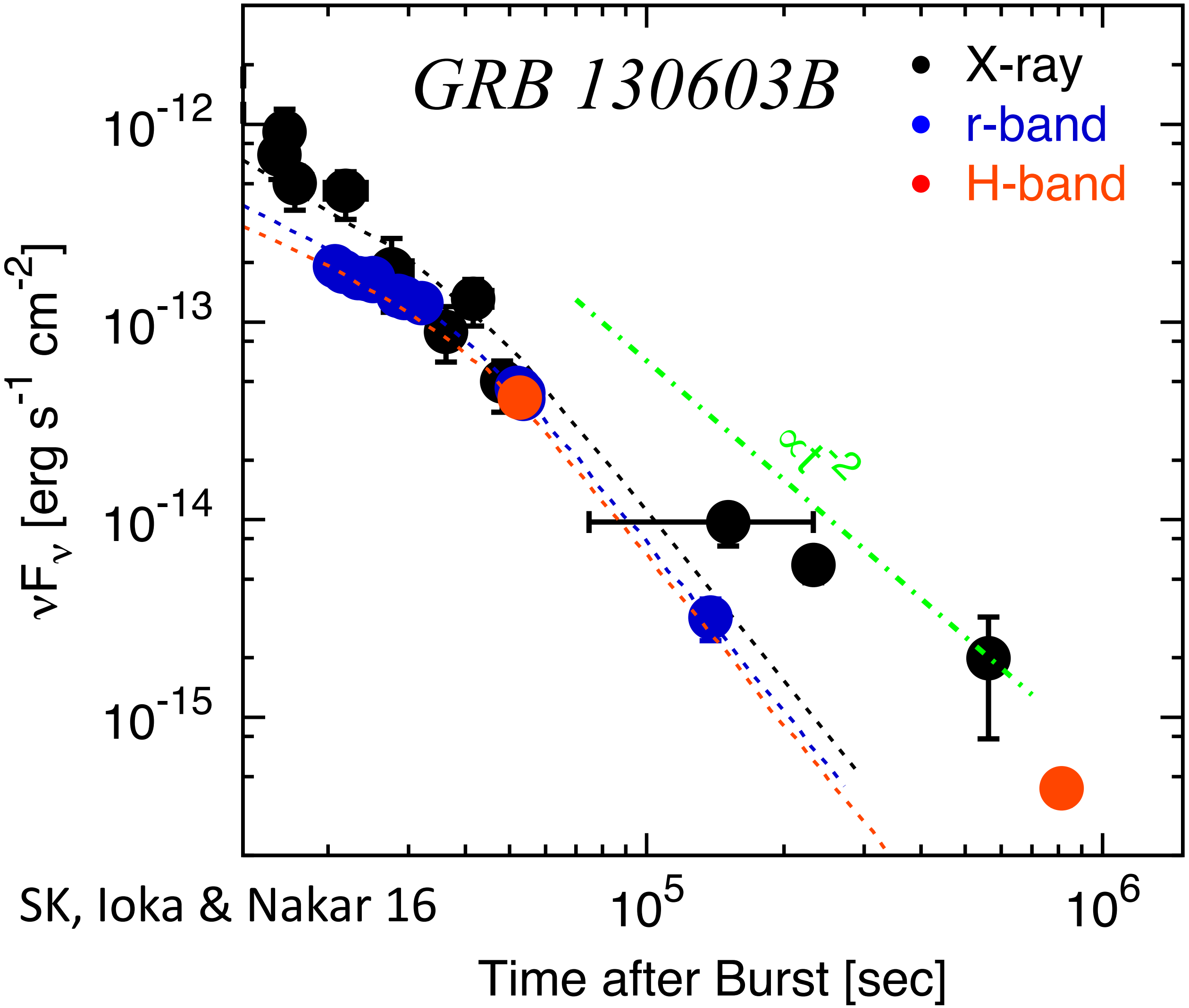
	$M_{ej}/M_\odot$	
GRB 050709	: ~ 0.1	Jin+ 16
GRB 060614	: ~ 0.25	Jin+ 15, Yang+ 15
GRB 130603B	: ~ 0.05 - 0.1	Hotokezaka+ 16, Barnes+ 16

Simulation

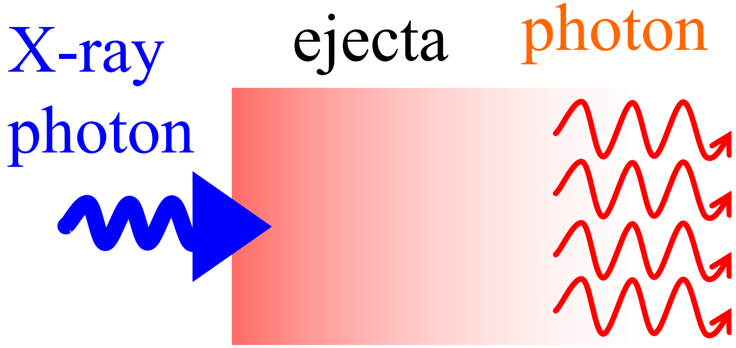
NS-NS	: ~ $10^{-4} – 10^{-2}$	Hotokezaka+ 13
BH-NS	: < 10^{-1}	Kyutoku+ 15

X-ray-powered Macronova ?

Fluxes of the X-ray and IR excesses are comparable. ⇨ **A single energy source?**



SK, Ioka & Nakar 16

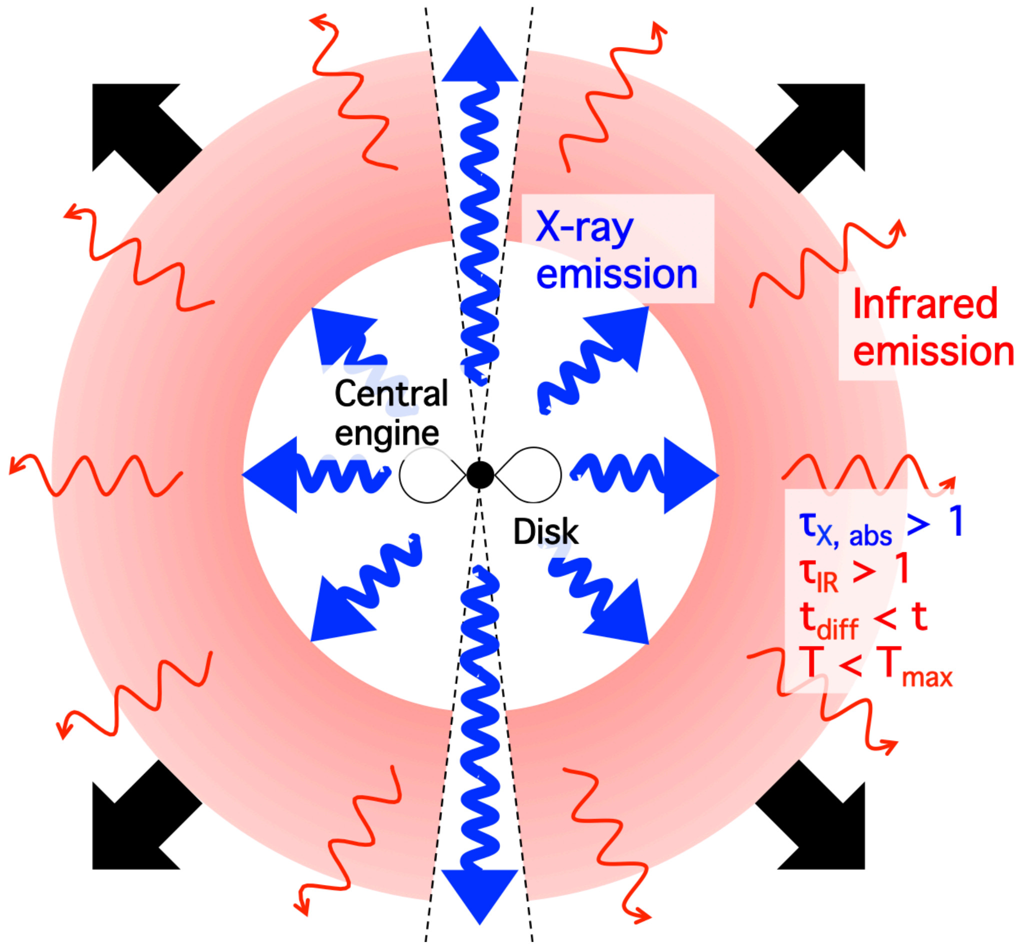


	F_{IR}/F_X
GRB 050709	~ 1
GRB 060614	~ 0.1
GRB 130603B	~ 0.4

Jin+ 16

X-ray-powered Macronova

The merger ejecta heated by the irradiation of X-ray emit thermal infrared radiation.



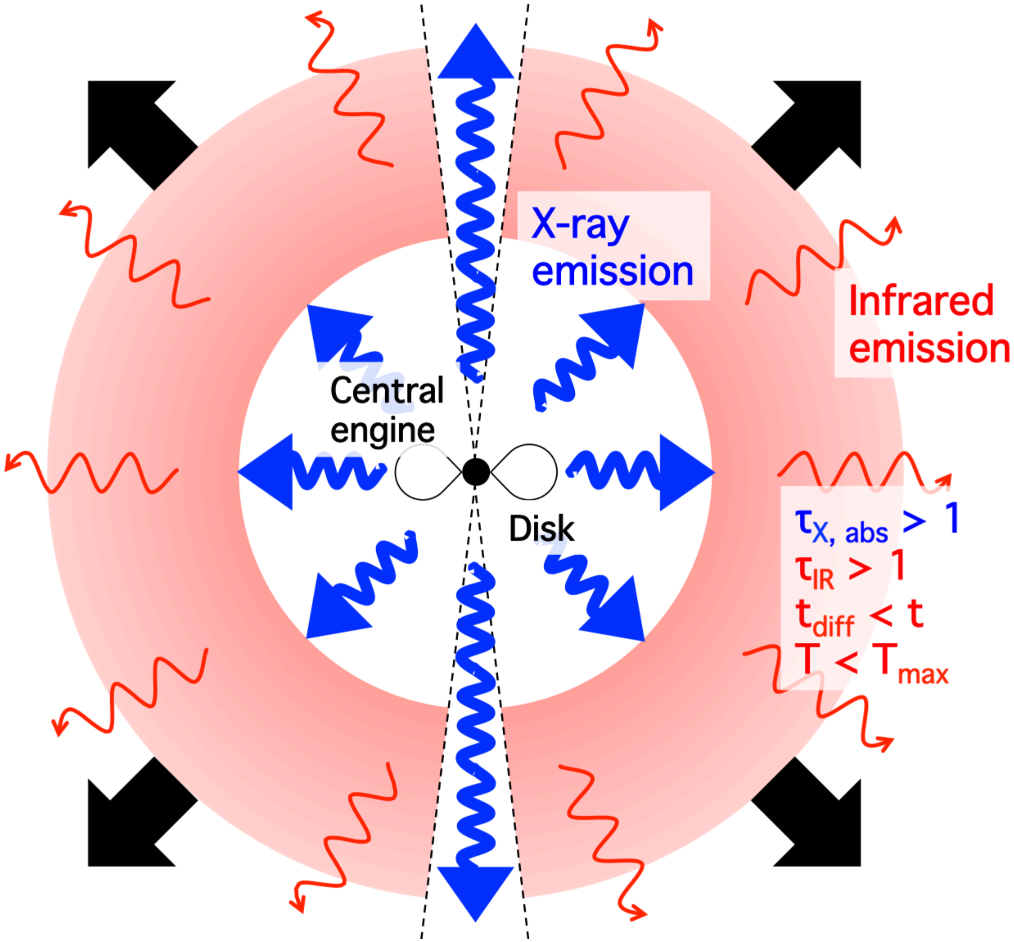
SK, Ioka & Nakar 16

Physical setups

- Isotropic X-rays are generated near the central source.
- The ejecta cover a fraction of solid angle.
- The line-of-sight to the source is clean for the observers.

X-ray-powered Macronova

The merger ejecta heated by the irradiation of X-ray emit thermal infrared radiation.



SK, Ioka & Nakar 16

Required conditions

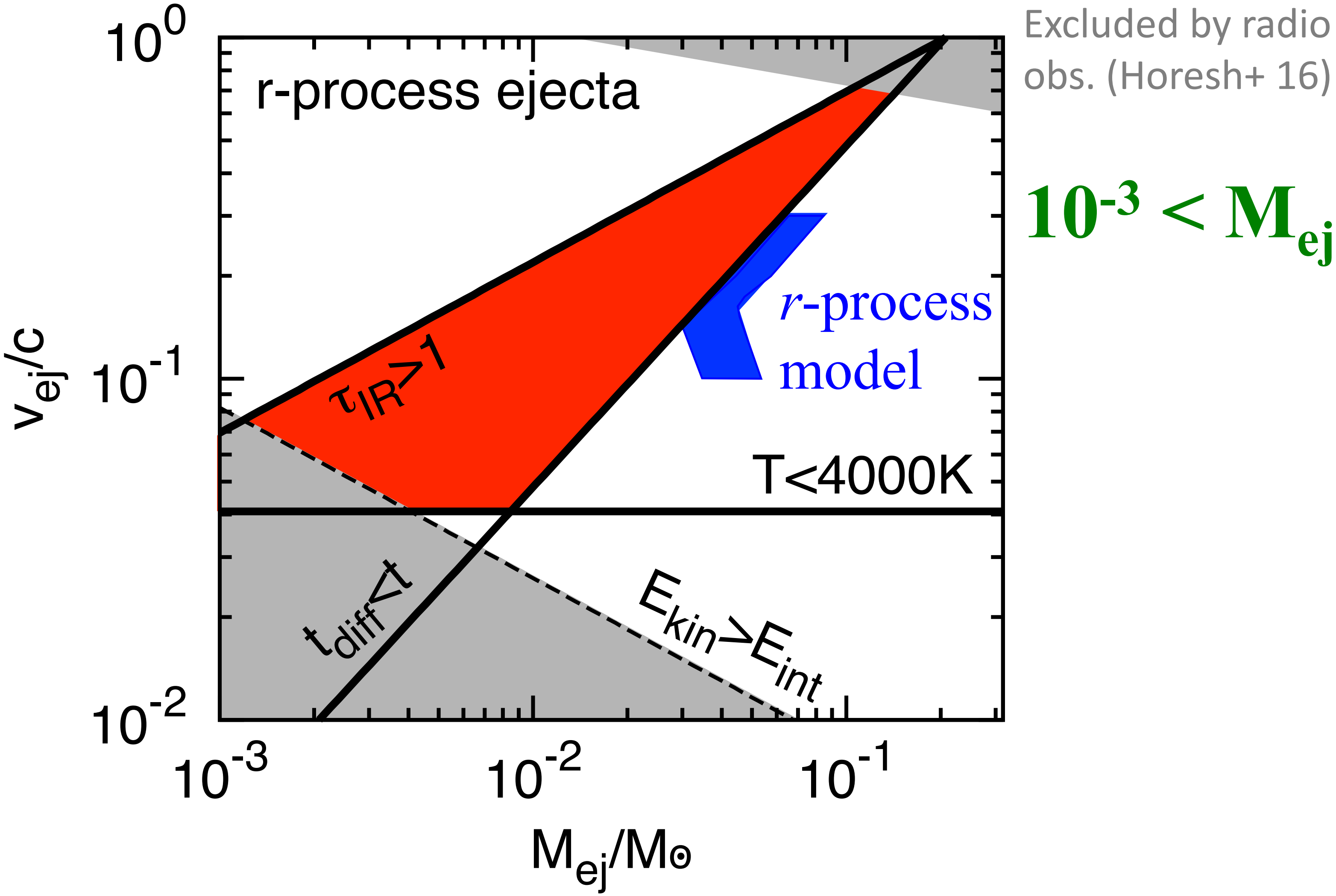
- Absorption of X-ray photons
  $\tau_X > 1$
- Thermalization
  $\tau_{IR} > 1$
- Escaping thermal photons
  $t_{diff} < t$
- Temperature
  $T < T_{max}$

Results

Broad ranges of the allowed parameter regions

SK, Ioka & Nakar 16

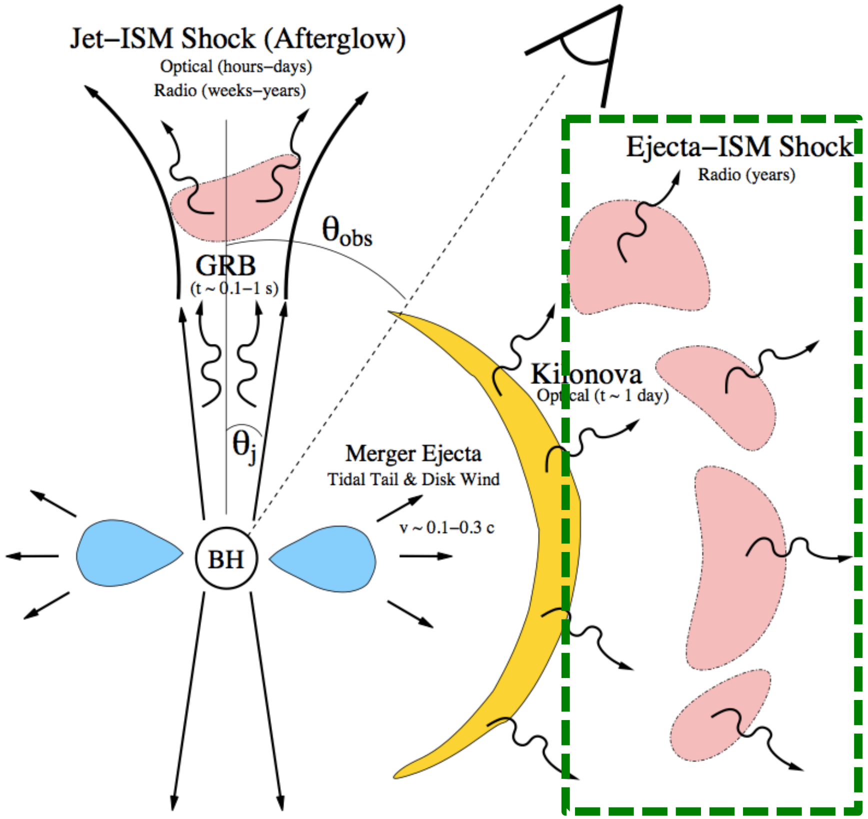
$\kappa_{\rm IR} = 10\ {\rm cm^2 g^{-1}}$

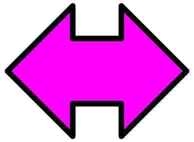


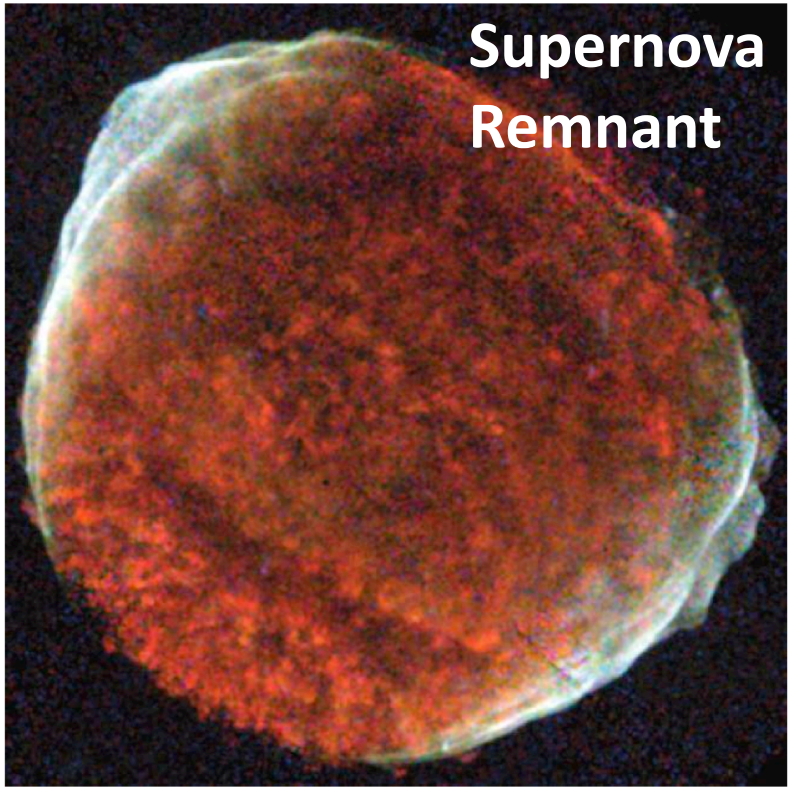
$10^{-3} < M_{ej}/M_{sun} < 10^{-1}$

Remnants of Merger Ejecta

Ejecta-ISM Shock







Metzger & Berger 12

Cassam-Chenai+ 08

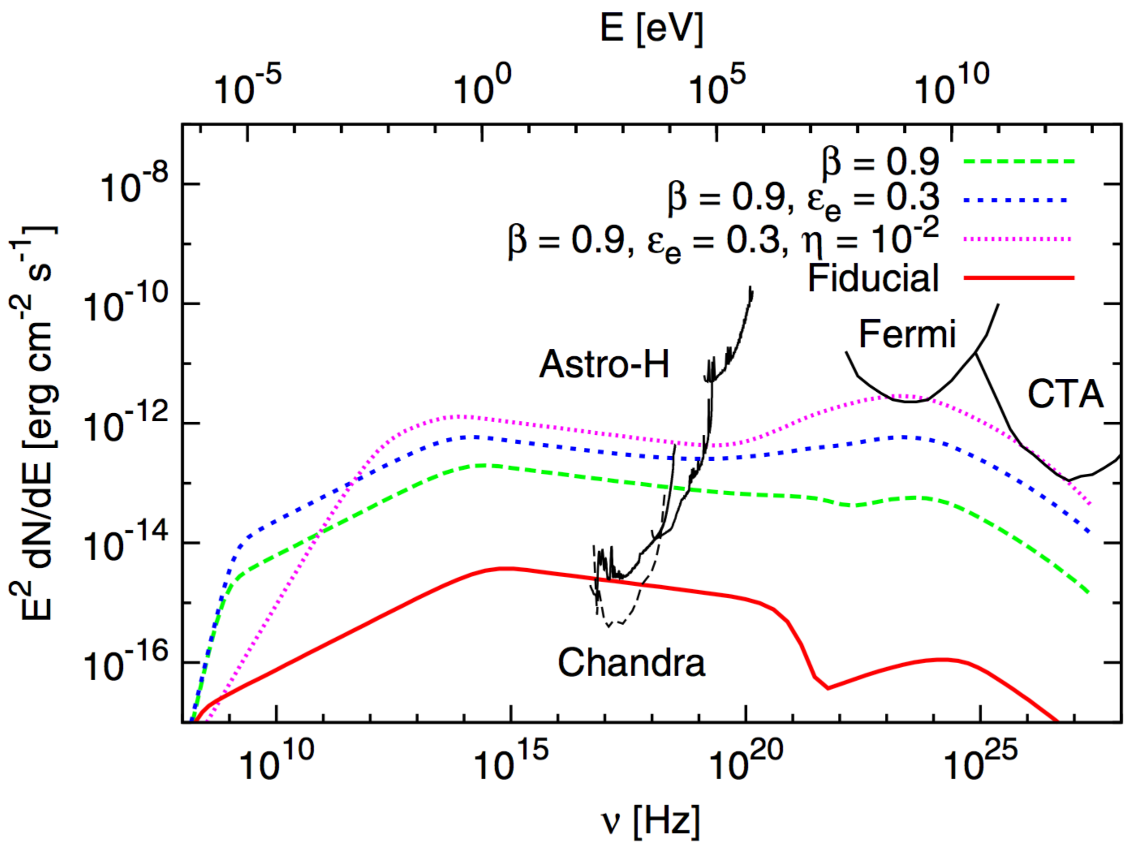
Free expansion → Sedov-Taylor phase

$$R_{\rm dec} = \left(\frac{3M_{\rm ej}}{4\pi n m_{\rm p}}\right)^{1/3} \sim 7\times10^{18}\left(\frac{M_{\rm ej}}{10^{-2}M_\odot}\right)^{1/3}\ {\rm cm}$$

$$t_{\rm dec} = \frac{R_{\rm dec}}{\beta_{\rm ej}} \sim 7\left(\frac{M_{\rm ej}}{10^{-2}M_\odot}\right)^{1/3}\left(\frac{\beta_{\rm ej}}{0.9}\right)^{-1}\ {\rm yr}$$

$$n = 10^{-2}{\rm cm}^{-3}$$

High Energy Radiation



Maximally allowed bolometric flux

$$F_{\rm max} = \frac{\epsilon_{\rm e} E_{\rm kin}}{4\pi d^2 t_{\rm dec}} \sim 2 \times 10^{-12} \left(\frac{M_{\rm ej}}{10^{-2} M_\odot}\right)^{2/3} \left(\frac{\beta_{\rm ej}}{0.9}\right)^3 \left(\frac{d}{100{\rm Mpc}}\right)^{-2} {\rm erg\ s^{-1} cm^{-2}}$$

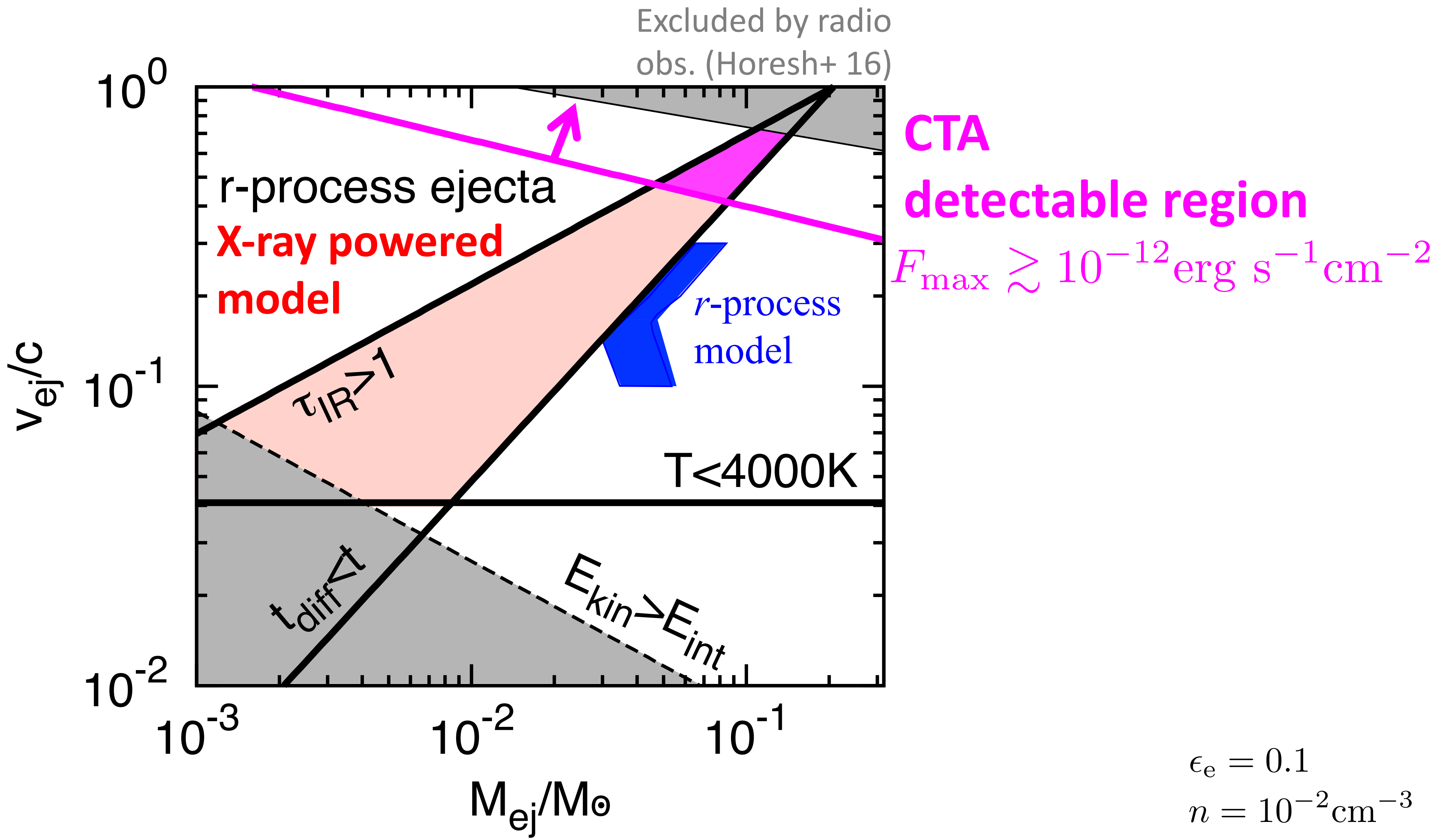
IC energy not affected by KN effect

$$E_{\rm IC} \lesssim 2 \times 10^{11} \left(\frac{M_{\rm ej}}{10^{-2} M_\odot}\right)^{1/15} \left(\frac{\beta_{\rm ej}}{0.9}\right)^{-1/5} {\rm eV}$$

$$\epsilon_{\rm e} = 0.1$$
$$n = 10^{-2} {\rm cm}^{-3}$$

GRB 130603B @100Mpc

CTA could give constraints on ejecta parameters.



$\epsilon_e = 0.1$

$n = 10^{-2} {\rm cm}^{-3}$

Summary

Gamma-ray Burst

Extended, Plateau, and scattered emissions could be detectable by current and planed detectors.

Macronova

X-ray-powered model explains IR excess and allow for broader parameter region even if the ejecta mass is $\sim 10^{-3}$ solar mass.

Remnant of Merger Ejecta

CTA could give constraints on the ejecta parameter space, which also explains the IR excess in X-ray-powered model.